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The Harmonic Order Tracking Analysis (HOTA) for the Diagnosis of Induction Generators Working Under Steady State Regime

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ABSTRACT

Improved fault diagnostic techniques in induction generators is a field of growing interest given the negative impact that unexpected breakdowns have on energy production and on the electrical system. New diagnostic techniques based on induction generator currents monitoring have recently been developed, but their use is still irrelevant despite the advantages that presents to detect electrical faults in the generator. This situation is due to the needs of high computing power and memory resources which are not available in embedded devices for on-line monitoring, also, to the use of signal processing techniques that generate volumes of data difficult to transfer to control centres, where they could be processed. This paper proposes the use of a recent methodology known as the harmonic order tracking analysis (HOTA) that solve these problems to for the diagnosis of induction generators. This approach can be implemented in low cost digital devices; the resultant patterns are very simple and easily interpretable, even by non-qualified personnel. Moreover, these patterns are characterized by a very low number of parameters, which make easy their transmission to remote control centres. In this paper the practical application of this approach is proposed using a laboratory test bed.

INTRODUCTION

Predictive maintenance systems play a key role in the profitability of electrical power plants. The detection of incipient faults prevents catastrophic failures, which, for example, in the case of wind groups have high repair costs and cause long periods of stoppage, with the subsequent economics losses for the not produced

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energy. In present wind farms, predictive maintenance is based on monitoring the vibration signals obtained from several accelerometers installed on key elements of the groups (gearbox, generator's bearing, etc.) [1]. But these techniques have two main drawbacks: on the one hand the amount of data generated by any group is difficult to be transmitted to the control centres. On the other hand, it is difficult to detect electrical faults in the generator. In recent years some research groups are working on the development of techniques for fault detection based on monitoring electrical magnitudes related to the generator [2]. Most of these researches are focused in monitoring stator and rotor currents. These methods have the advantage of not requiring the installation of additional sensors, which can be a source of failure. In fact, the currents, as they are necessary for performing the functions of control and protection of the group and for measuring the produced energy, are always sampled. Moreover, monitoring generator currents enable for detection of faults in mechanical parts providing complementary diagnostic information to the vibration analysis, increasing the reliability of the diagnostic systems.

However, the developments in the fault diagnosis through the analysis of the current have not had a significant implantation in the currently operating electrical power plants. Its limited implementation in operating facilities may be due to practical problems, because they have been developed regardless the restrictions imposed by the exploitation form the electrical power plants:

- Most of the developed techniques require a much greater computing power than that provided by the equipment installed in the groups.
- The techniques require high sampling rates and acquisition times that produce a very large volume of data. This makes not feasible the transmission of these data to remote monitoring.

This paper proposes the application of the fault diagnosis technique known as harmonic order tracking analysis (HOTA) [3] based on current's monitoring suitable for generators, which aims to address the problems outlined above, and offers additional advantages:

- The results of each analysis are synthesized in a very small number of values (fifteen real values) which greatly facilitates its transmission to centralized dispatch centres, where it can be analysed and stored for historical trend analysis.
- The algorithm can be implemented in low-cost equipment [4-5], such as DSP, PLC and FPGA.
- The fault components appear always located at the same position regardless the speed. Hence it is not required additional computing process by personnel or by expert diagnostic systems to identify the fault components.

In this paper, based on the theoretical background presented in [3] HOTA is applied to the diagnosis of the induction generators working under steady state using the signals obtained in a laboratory test bench. So, the structure of this paper is as follows. Section 2 illustrates the experimental validation of the proposed method. Finally, in section 4 the conclusions of the work are presented.

EXPERIMENTAL VALIDATION OF THE PROPOSED METHOD

The experimental validation has been performed using two commercial 1.5 kW cage induction machines (Appendix –Siemens) working as induction generators and a permanent magnet synchronous machine (PMSM) (Appendix- ABB) as simulator of the wind turbine. One of those induction machine (IM) remains in healthy conditions whereas in the other one an artificially rotor broken bar fault has been performed (Fig. 2). Similar results can be obtained when an induction wound rotor generator with winding unbalances is tested. In this section the test bench is described and the results obtained are displayed.

Figure 1. Rotor with an artificially forced broken bar.

Test Bench

The test bench used is depicted in Fig. 3. The IM tested is connected directly to the mains power supply. The PMSM is controlled by ABB's servo driver, model ACSM1-04AS-024A-4+L516. It allows to work with the PMSM in torque control, speed control or position control precisely in close loop using the signal of the resolver coupled to the PMSM. It is also equipped with a module (FEN21) which outputs an electronically generated encoder signal with a programmable resolution up to 1024 pulses per revolution. The tests have been carried out using the speed control and an encoder resolution of 720 pulses per revolution to compute the rotor's angular position (15).

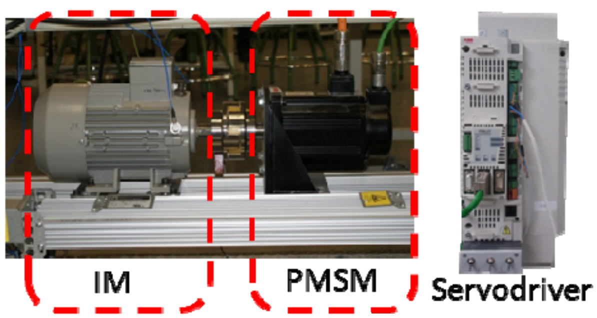

Figure 2. Test bench used. Induction machine (IM) coupled to a permanent magnet synchronous machine (PMSM). Servodriver (right) used to control the PMSM.

The stator current has been measured using a current clamp (*20*A, *0-10*kHz, *1*A/*1*mV, precision class 2). This clamp has been connected to a digital oscilloscope, model Yokogawa DL750, using an analogue voltage input module (ref. 701250, *10*Ms, *12* bits). Likewise, the pulses generated by the module FEN 21 of the servodriver are sampled with a similar module of the oscilloscope. A sampling rate of *100* kHz has been used to properly capture the encoder pulses and to avoid the use of anti-aliasing filters. On the other hand, tests of *100* seconds have been performed to be able to resolve the fault harmonic components even under very low slip conditions. As a result, a total number of 107 samples per signal (x2 signals: current and encoder) has been acquired.

Experimental Tests

Several tests with the healthy and the faulty machine have been performed in order to assess the validity of the new method proposed. In this paper, the four tests presented in Table 1 have been performed.

The test (a) has been carried out with a healthy machine, so that the results of the other tests can be compared with the healthy state, validating the proposed method. In the other three tests the machine with a rotor broken bar has been used. Additionally, the fault frequencies (f_{LSH} and f_{USH}) have been included in Table 1. The diagnostic decision depends on the presence at these frequencies of harmonics components higher than the thresholds established in the technical literature. Nevertheless, the main drawback in traditional MCSA methods is that the fault frequencies must be computed for every working conditions of the generator. Hence, the speed information must be stored with the current's spectrum to identify the fault.

Table 1. Experimental tests.

	Speed (rpm)	f_1(Hz)	f_{USH} (Hz)	f_{LSH} (Hz)
(a)	3100	50	Healthy	Healthy
(b)	3050	50	48.31	51.67
(c)	3100	50	46.67	53.33
(d)	3150	50	45.01	54.99

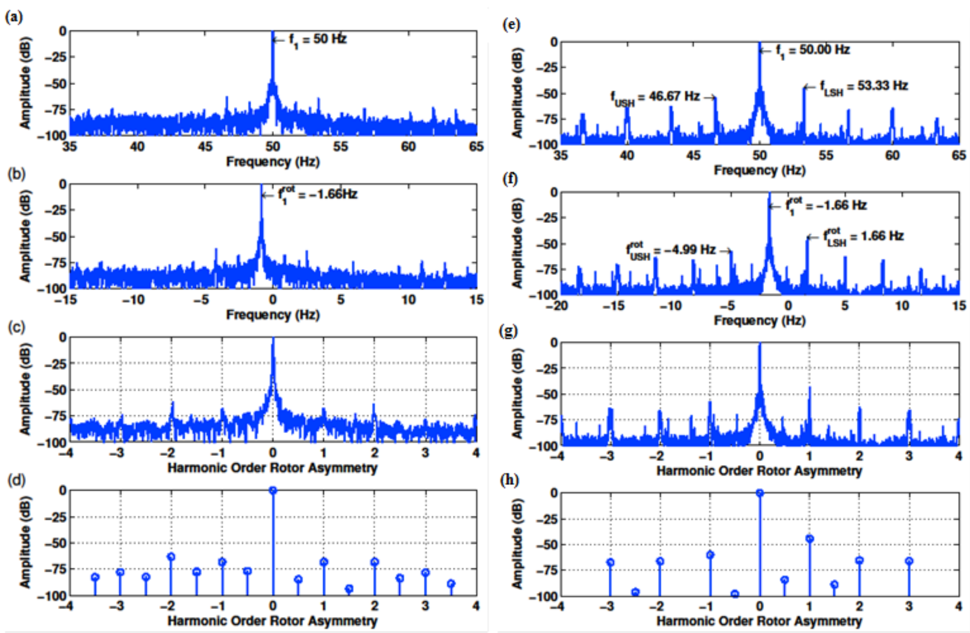

Figure 3. (Left) Results of the test (a) in Table I (Healthy machine). a) Current's spectrum. b) Current's spectrum in the rotor frame. c) Harmonic Order Spectrum and d) Reduced harmonic order spectrum obtained with the proposed method. (Right) Results of the test (c) in Table I (Faulty Machine, 3100 r.p.m). e) Current's spectrum. f) Current's spectrum in the rotor frame. g) Harmonic Order Spectrum and h) Reduced harmonic order spectrum obtained with the proposed method

The results of two different tests (healthy and faulty machine) are shown in Figure 3. In this figure the top plots (a) display the traditional MCSA results. In this case just a current's FFT and a Hanning window are used. As expected, although the frequency supply is the same for each test, the fault harmonic components appear at different positions depending on the generator's speed. Actually, for every test, the automatic diagnostic system and/or the personnel needs additional information (generator's speed) to compute the exact fault frequencies. The amplitude of the fault components at these frequencies will be compared with predefined thresholds or with previous values to identify the presence or absence of the fault.

The second plot (Figure 3.b, f) is the current's spectrum expressed in the rotor frame. In this case, the mains component appears at a distance $sf_1 < 0$ from the origin. This distance is used to apply the change of scale proposed in HOTA, obtaining the results shown in (Figure 3c,g). In this figures the fault components appear always directly localized at the integer orders of k. This feature greatly facilitates the diagnostic process because both the maintenance personnel or automatic diagnostic system don't have to take into account the working conditions. Neither additional information nor mathematical calculus are required to resolve which components are due to the fault because they are located always at the same positions, the integer harmonic orders.

Finally, the information about the fault can be summarized in just 15 points as can be seen in Figure 3 d, h. This not only reduces the memory requirements but also reduces the information that must be transmitted through networks to remote systems. Moreover, all the results can be displayed in a single plot in order to facilitate the comparison with previous states, other working conditions, theoretical thresholds or even with results of other machines to determine the presence or absence of a fault, as displayed in Figure 4.

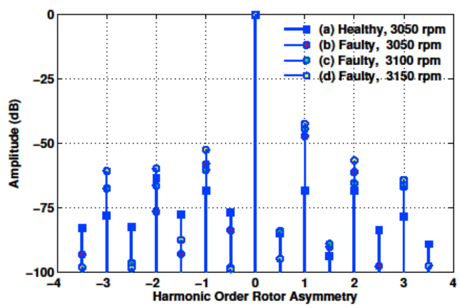

Figure 4. Superposition in a single plot of the Reduced Harmonic Order Spectrum of the currents in the four test of table 1.

CONCLUSIONS

In this paper the application of HOTA for diagnosis of induction generators working in steady state regime has been proposed which offers several advantages. The fault information in the current spectrum is located always at the same positions regardless of the speed, generator's pole pairs, frequency supply, etc., so simplifying and clarifying the fault diagnostic process, enough to perform the fault diagnosis either by automatic systems or by maintenance personnel. Moreover, it can be implemented in low-cost equipment. Finally, the proposed method generates a set of just 15 points, which greatly facilitates the transmission of diagnostic data to centralized control centers.

APPENDIX

Siemens' three-phase induction machine, star connection. Rated characteristics:

P = 1.5 kW, f = 50 Hz, U = 400 V, I = 3.3 A, n = 2860 rpm, and cosφ= 0:85.

ABB's permanent magnet synchronous machine (PMSM). Rated characteristics:

P = 4.9 kW, f = 200 Hz, T = 15.5 Nm, Tp = 47.7 Nm, I = 14.4 A, Ip = 43.4 A, and n = 3000 rpm

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